UDC 681.5.09

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AN IMPROVED FAULT-TOLERANT ALGORITHM FOR A GYROSCOPIC SENSORS UNIT

An improved fault tolerant algorithm is presented. Its mathematical models as well as its implementation are discussed in this work. The algorithm's effectiveness has been proved by means of computer program and applied to a gyroscopic sensors unit (GSU). The improved fault-tolerant algorithm has the ability to perform a complete diagnosis of the GSU, constantly monitoring its state by means of several mathematical models, determining the possible existence of a fault in the unit. Once a fault in the unit has occurred, the algorithm is able to find where the fault is located; allowing us to define what kind of fault has appeared in the unit and this diagnosis can lead us to perform the proper corrective actions to recover the optimal performance in the GSU.

Keywords: *fault-tolerant system, fault-tolerant algorithm, gyroscopic sensors unit.*

Introduction

Building reliable systems is one of the main challenges that is faced by software developers and they have been concerned with dependability issues since the first day a system was built and deployed [1]. Many changes in this matter have been occurred, including the nature of faults and failures, the complexity of systems, the services that they deliver, the way society uses them and obviously, in theory, approaches, and technology [2]. But the need to deal with various threats such as failed components, deteriorating environments, human mistakes, intrusions, components mismatches or software bugs; is in the core of software, research, and development. Errors always happen in spite of all the efforts to eliminate faults that might cause them, so several fault tolerant mechanisms and approaches have been investigated by researchers and used in various fields of technology and applied industrial solutions [3-5]. Unfortunately, these solutions are more focused on the implementation, ignoring other development phases as a fault tolerant support system. This creates a dangerous gap between the implementation and the reliability of a system. As consequence of this, there is an increasing number of situations in which fault tolerant support has been undermined, decreasing gravely the systems' reliability.

Fault tolerant support needs to be explicitly included into every design but especially where any malfunction in the system could lead to seriously have economical lost but even worst to have lost of human lives.

As current software engineering practices tend to think only about normal behavior, assuming that all faults can be removed during development phase, improved algorithms or methods must be developed to support explicit handling of abnormal situation. Furthermore, every developed system should be enriched with a fault tolerant support means.

Looking forward to meet this challenge, this work presents an improved fault tolerant algorithm support with the specific task to increase the reliability of a gyroscopic sensors unit (GSU).

1. Diagnostic model for the GSU

The GSU is built by three gyroscopic sensors, two angular velocity sensors, angular velocity sensor 1 (AVS_1) and angular velocity sensor 2 (AVS_2), and one angle sensor (AS) in order to guaranty a diagnosis in the GSU, as it is shown in Fig. 1.

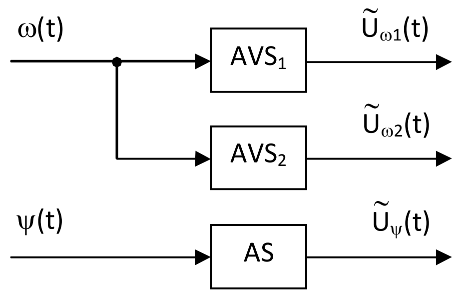

Fig. 1. Structural scheme of GSU

The sensors' characteristic equations are represented in (1):

$$\begin{aligned} &\tilde{U}_{\omega 2}(t)=\tilde{K}_{\omega 2}\cdot\omega(t)+U_0^{\omega 2}, \\ &\tilde{U}_{\omega 1}(t)=\tilde{K}_{\omega 1}\cdot\omega(t)+U_0^{\omega 1}, \\ &\tilde{U}_{\psi}(t)=\tilde{K}_{\psi}\cdot\psi(t)+U_0^{\psi}, \end{aligned} \tag{1}$$

where $\tilde{U}_{\omega 2}(t)$ – AVS_2 output;

$\tilde{U}_{\omega 1}(t)$ – AVS_1 output;

$\tilde{U}_{\psi}(t)$ – AS output;

$\tilde{K}_{\omega 2}$, $\tilde{K}_{\omega 1}$, $\tilde{K}_{\psi}$, – sensors' transfer–coefficient;

$\omega(t)$ – angular velocity;

$\psi(t)$ – angle position;

$U_0^{\omega 2}$, $U_0^{\omega 1}$, U_0^{ψ} – drift values from zero.

The fact of detecting the existence of a fault in the GSU leads to find its place (which sensor is the faulty one), class and kind of the fault, in Fig. 2 is shown the general scheme for the implemented methodology.

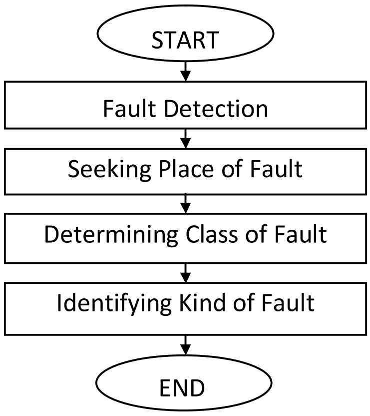

Fig. 2. Methodology's general scheme

The fault tolerant algorithm can identify 32 kinds of faults, classified in 4 classes. According to the study and analysis of the GSU in [6], there are very specific faults in the unit, leading us to understand the behavior of the system or even better, the sensors' behavior and improve and extend the algorithm shown in [7]. The kinds of faults are determined by the letter "d" and are following defined:

d1 – positive power supply cable broken;

d2 – negative power supply cable broken;

d3 – signal cable broken;

d4 – irremovable positive voltage drift;

d5 – removable positive voltage drift;

d6 – removable negative voltage drift;

d7 – irremovable negative voltage drift;

d8 – removable decreased transfer coefficient;

d9 – irremovable decreased transfer coefficient;

d10 – reoriented transfer coefficient;

d11 – reoriented and removable decreased transfer coefficient;

d12 – reoriented and irremovable decreased transfer coefficient;

d13 – removable decreased transfer coefficient with irremovable positive voltage drift;

d14 – removable decreased transfer coefficient with removable positive voltage drift;

d15 – irremovable decreased transfer coefficient with irremovable positive voltage drift;

d16 – irremovable decreased transfer coefficient with removable positive voltage drift;

d17 – reoriented transfer coefficient with irremovable positive voltage drift;

d18 – reoriented transfer coefficient with removable positive voltage drift;

d19 – reoriented and removable decreased transfer coefficient with irremovable positive voltage drift;

d20 – reoriented and removable decreased transfer coefficient with removable positive voltage drift;

d21 – reoriented and irremovable decreased transfer coefficient with irremovable positive voltage drift;

d22 – reoriented and irremovable decreased transfer coefficient with removable positive voltage drift;

d23 – removable decreased transfer coefficient with irremovable negative voltage drift;

d24 – removable decreased transfer coefficient with removable negative voltage drift;

d25 – irremovable decreased transfer coefficient with irremovable negative voltage drift;

d26 – irremovable decreased transfer coefficient with removable negative voltage drift;

d27 – reoriented transfer coefficient with irremovable negative voltage drift;

d28 – reoriented transfer coefficient with removable negative voltage drift;

d29 – reoriented and removable decreased transfer coefficient with irremovable negative voltage drift;

d30 – reoriented and removable decreased transfer coefficient with removable negative voltage drift;

d31 – reoriented and irremovable decreased transfer coefficient with irremovable negative voltage drift;

d32 – reoriented and irremovable decreased transfer coefficient with removable negative voltage drift.

The following hypothesizes have been defined in developing the diagnostic process for the GSU.

1. Only can be one faulty sensor at the moment of diagnose.
2. Each sensor could present one or two kind of faults at a time.
3. Only "Shift" and "Coefficient" fault type can occur at a time in one sensor.
4. The input signal must be of the kind to determine the types of faults above described.
5. A kind of fault can independently appear from each others.

2. Algorithm's Mathematical Model

2.1. Fault and Place Detection

The GSU is constantly monitored. The mathematical model for this monitoring is following discussed. Fig. 3 shows the block diagram for the monitoring procedure and its specific stages to detect a fault and its place.

Diagram application is ahead explained.

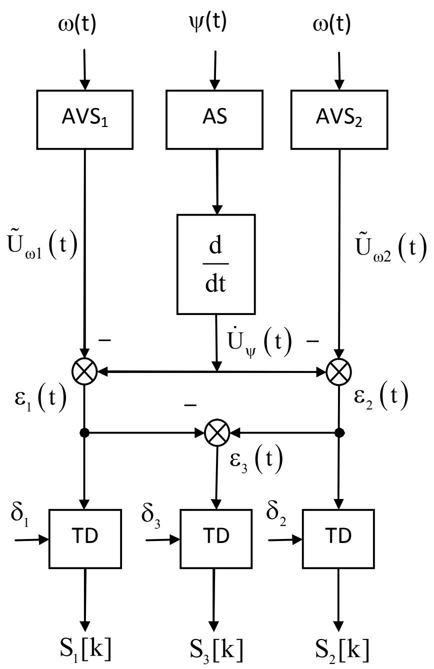

Fig. 3. Fault and place detection diagram

The errors in Fig. 3 are represented by (2).

$$\varepsilon_1(t) = \tilde{U}_{\omega 1}(t) - \dot{U}_{\psi}(t),$$
$$\varepsilon_2(t) = \tilde{U}_{\omega 2}(t) - \dot{U}_{\psi}(t), \quad (2)$$
$$\varepsilon_3(t) = \tilde{U}_{\omega 2}(t) - \tilde{U}_{\omega 1}(t),$$

where $\varepsilon_1(t)$ – error between AVS_1 and AS;
$\varepsilon_2(t)$ – error between AVS_2 and AS;
$\varepsilon_3(t)$ – error between AVS_2 and AVS_1;
$\tilde{U}_{\omega 2}(t)$ – AVS_2 output;
$\tilde{U}_{\omega 1}(t)$ – AVS_1 output;
$\dot{U}_{\psi}(t)$ – derived AS output.

Threshold Device (TD) is in charge to determine the existence of a fault in the GSU, monitoring the errors and a threshold value δ_{si}, represented in (3).

$$S_1[k] = \left\{ \left| \tilde{U}_{\omega 1}[k] - \dot{U}_{\psi}[k] \right| > \delta_{s1} \right\},$$
$$S_2[k] = \left\{ \left| \tilde{U}_{\omega 2}[k] - \dot{U}_{\psi}[k] \right| > \delta_{s2} \right\}, \quad (3)$$
$$S_3[k] = \left\{ \left| \tilde{U}_{\omega 2}[k] - \tilde{U}_{\omega 1}[k] \right| > \delta_{s3} \right\},$$

where $S_i[k]$ – indicator of presence of fault;
$\tilde{U}_{\omega 1}[k]$, $\tilde{U}_{\omega 2}[k]$, $\dot{U}_{\psi}[k]$ – sensor's output;
δ_{si} – threshold value.

Table 1

Indicator of faults' place

	$\tilde{U}_{\omega 2}$	$\tilde{U}_{\omega 1}$	$\dot{U}_{\psi}$
S_1	0	1	1
S_2	1	0	1
S_3	1	1	0

The subscript i refers to each sensor according to S_1, S_2 and S_3. In order to find the place of fault, we use the S_i indicators; the Table 1 shows the possible combinations of the indicators when a fault has occurred.

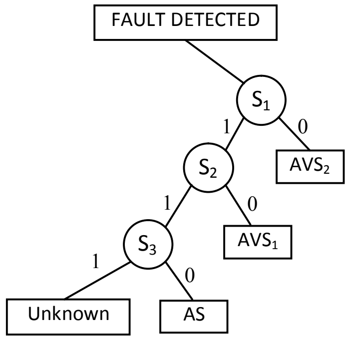

Fig. 4. Dichotomic tree to find the place of fault

The dichotomic tree for this procedure is shown in Fig. 4. According to Table 1 three statements are defined for determining the faults' place.

If $S_1 = 0$ THEN fault is in AVS_2,
If $S_2 = 0$ THEN fault is in AVS_1,
If $S_3 = 0$ THEN fault is in AS.

2.2. Determining the Class of Fault

The fault tolerant algorithm can identify 32 kinds of faults for each sensor, classified into four classes following explained.

Class "Broken"

This class is characterized by constants voltages at the output of the faulty sensor, the mathematical model for determining this class is shown in (4) and (5).

$$Z_{Bi}(n) = \left\{ \sum_{n=1}^{k} \tilde{U}_{Bi}(n+1) - \tilde{U}_{Bi}(n) > \delta_{Bi} \right\}, \quad (4)$$

where $Z_{Bi}(n)$ – indicator of class "Broken";
$\tilde{U}_{Bi}(n)$ – output sample of the faulty sensor;
δ_{Bi} – threshold value for class "Broken".

$$Z'_{Bi} = \{N > \rho_B\}, \quad (5)$$

where Z'_{Bi} – indicator of reliability for class "Broken";
N – counter of truly results of Z'_{Bi};
ρ_B – threshold of reliability for class "Broken".

Class "Drift"

This class is defined by a constant voltage drift in the output of the faulty sensor. First it is calculated the mean value of the error signals with (6).

$$\Delta\varepsilon_D = \frac{\varepsilon_{D1} + \varepsilon_{D2}}{2}, \quad (6)$$

where $\Delta\varepsilon_D$ – average value of the error out of tolerance;

ε_{D1} – first error signal out of tolerance;

ε_{D2} – second error signal out of tolerance.

Then, we apply (7) in order to know if the drift voltage is constant.

$$Z_{Di}(n) = \left\{ \sum_{n=1}^{k} \left| \Delta\varepsilon_D(n+1) - \Delta\varepsilon_D(n) \right| > \delta_{Di} \right\}, \quad (7)$$

where $Z_{Di}(n)$ – indicator of class "Drift";

$\Delta\varepsilon_D$ – sample of the average value of the two errors out of tolerance;

δ_{Di} – threshold value for class "Drift".

After that, we use (8) as indicator of reliability for this class.

$$Z'_{Di} = \{N > \rho_D\}, \quad (8)$$

where Z'_{Di} – indicator of reliability for class "Drift";

N – counter of truly results of Z'_{Di};

ρ_D – threshold of reliability for class "Drift".

Classes "Coefficient" and "Drift–Coefficient"

These classes are characterized by a constant or variable difference value between the right transfer coefficient and that one that is wrong. For obtaining $\tilde{U}_c$ we apply (9).

$$\tilde{U}_c = \frac{U_1 + U_2}{2}, \quad (9)$$

where $\tilde{U}_c$ – average value of the two sensors that do work well;

U_1 – value of the first sensor that works well;

U_2 – value of the second sensor that works well.

It is necessary to obtain the average change in the transfer coefficient by means of (10).

$$K(n) = \frac{\hat{U}_i(n)}{\tilde{U}_c(n)}, n \in 1 \ldots k, \quad (10)$$

where K(n) – change in transfer coefficient values;

$\tilde{U}_c(n)$ – average values of the two sensors that do work well;

$\hat{U}_i(n)$ – values of the faulty sensor.

The average of K(n) is obtained by (11), besides obtaining the indicators for each class of fault by (12) and (13).

$$\Delta K = \frac{1}{k}\sum_{n=1}^{k} K(n), \quad (11)$$

where ΔK – average value of changed coefficient;

K(n) – changed transfer coefficient values.

$$Z_{Ci}(n) = \{-\delta_{Ci} < |K(n) - \Delta K| < \delta_{Ci}\}, n \in 1 \ldots k, \quad (12)$$

where $Z_{Ci}(n)$ – indicator of class "Coefficient";

δ_{Ci} – threshold value for class "Coefficient".

$$Z_{Mi}(n) = \{-\delta_{Mi} < |K(n) - \Delta K| < \delta_{Mi}\}, n \in 1 \ldots k \quad (13)$$

where $Z_{Mi}(n)$ – indicator of class "Drift–Coefficient";

δ_{Mi} – threshold value for class "Drift–Coefficient".

Finally, indicators of reliability for these classes are applied, represented by (14) and (15).

$$Z'_{Ci} = \{N > \rho_C\}, \quad (14)$$

where Z'_{Ci} – indicator of reliability for "Coefficient";

N – counter of truly results of Z'_{Ci};

ρ_C – threshold of reliability for class "Coefficient".

$$Z'_{Mi} = \{N > \rho_M\}, \quad (15)$$

where Z'_{Mi} – indicator of reliability for "Drift–Coefficient";

N – counter of truly results of Z'_{Mi};

ρ_M – threshold of reliability for class "Drift–Coefficient".

The dichotomic tree for defining the class of fault is depicted in Fig. 5.

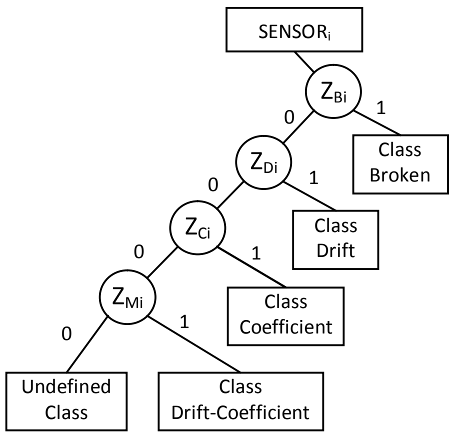

Fig. 5. Dichotomic tree to determine fault's class

2.3. Defining the Kind of Fault

According to the general scheme shown in Fig. 2, identification of the kind of fault should carry out after defining the class of fault.

Type of fault "Broken"

In this kind of fault, we have three different types (d1, d2 and d3) and they are represented by the statements in (16) which define the corresponding kind of fault. We use a tolerance value called δ_{tb}.

$$Z_{1+} = \{U_{min} + \delta_{tb} > U_\delta > U_{min} - \delta_{tb}\},$$
$$Z_{1-} = \{U_{max} + \delta_{tb} > U_\delta > U_{max} - \delta_{tb}\}, \quad (16)$$
$$Z_{1s} = \{\delta_{tb} > U_\delta > -\delta_{tb}\},$$

where Z_{1+} – indicator for positive power supply fault;
Z_{1-} – indicator for negative power supply fault;
Z_{1s} – indicator for signal power supply fault;
U_δ – faulty sensor output voltage value;
U_{max} – maximum voltage value;
U_{min} – minimum voltage value;
δ_{tb} – threshold value for this kind of fault.

The Fig. 6 shows the dichotomic tree to define what kind of fault "Broken" is. This kind of fault is unrecoverable.

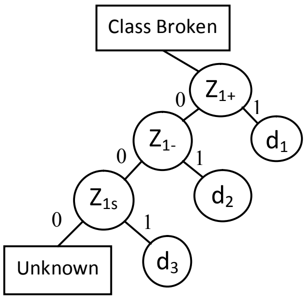

Fig. 6. Dichotomic Tree for faults in class "Broken"

Type of fault "Drift"

This kind of fault has four different types (d4–d7) as it is depicted in the dichotomic tree for this kind of fault in Fig. 7.

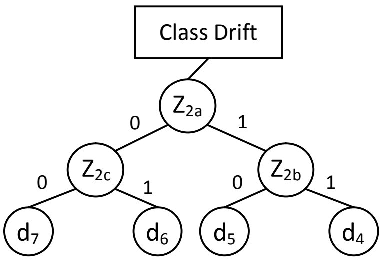

Fig. 7. Dichotomic Tree for faults in class "Drift"

The statements in (17) represent each case and their indicators for determining this kind of fault.

$$Z_{2a} = \{\Delta\varepsilon > 0\},$$
$$Z_{2b} = \{\Delta\varepsilon > \delta_D\}, \quad (17)$$
$$Z_{2c} = \{\Delta\varepsilon < -\delta_D\},$$

where Z_{2a} – positive drift indicator;
Z_{2b} – irremovable positive drift indicator;
Z_{2c} – irremovable negative drift indicator;
δ_D – threshold value for irremovable drift;
$\Delta\varepsilon$ – average value of ε_1 and ε_2.

Type of fault "Change in Transfer Coefficient"

In this kind of fault, there are five different cases defined by d8 – d12.

Their corresponding statements are shown in (18).

$$Z_{3a} = \{-K_i + 1\%K_i{}^3\Delta K^3 - K_i\},$$
$$Z_{3b} = \{0 < \Delta K < K_i - 1\%K_i\}, \quad (18)$$
$$Z_{3c} = \{\Delta K < 10\%K_i\},$$
$$Z_{3d} = \{\Delta K > -10\%K_i\},$$

where Z_{3a} – reorientation of transfer coeff. indicator;
Z_{3b} – decreased transfer coefficient indicator;
Z_{3c} – removable decreased coefficient indicator;
Z_{3d} – reoriented and removable decreased transfer coefficient indicator;
K_i – coefficient value of the faulty sensor in normal state.

The dichotomic tree for this process is shown in Fig. 8.

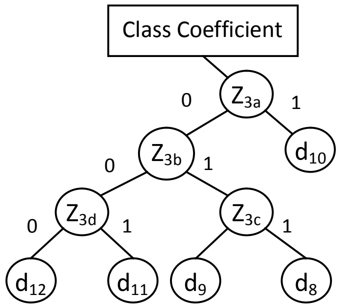

Fig. 8. Dichotomic Tree for faults in class "Coefficient"

Type of fault "Drift-Coefficient"

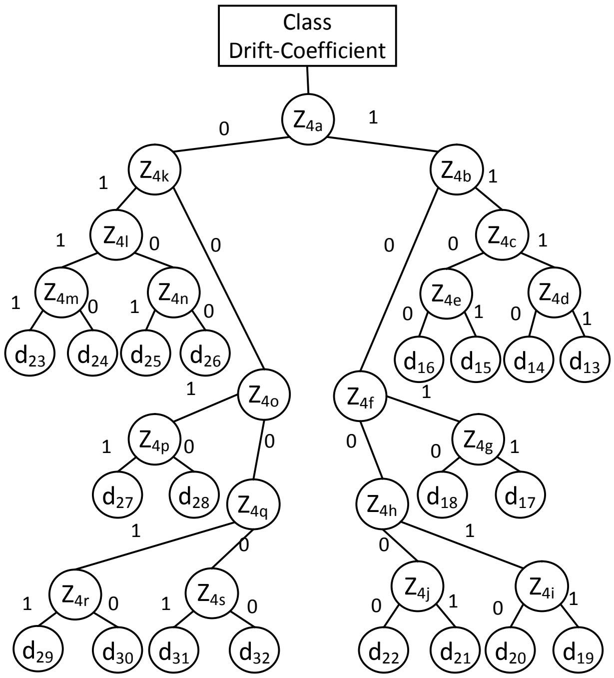

Fig. 9. Dichotomic Tree for faults in class "Drift-Coefficient"

Dichotomic tree for determining these kinds of faults is depicted in Fig.9. A test for the algorithm can be seen in Fig. 10, it was used the platform in [3].

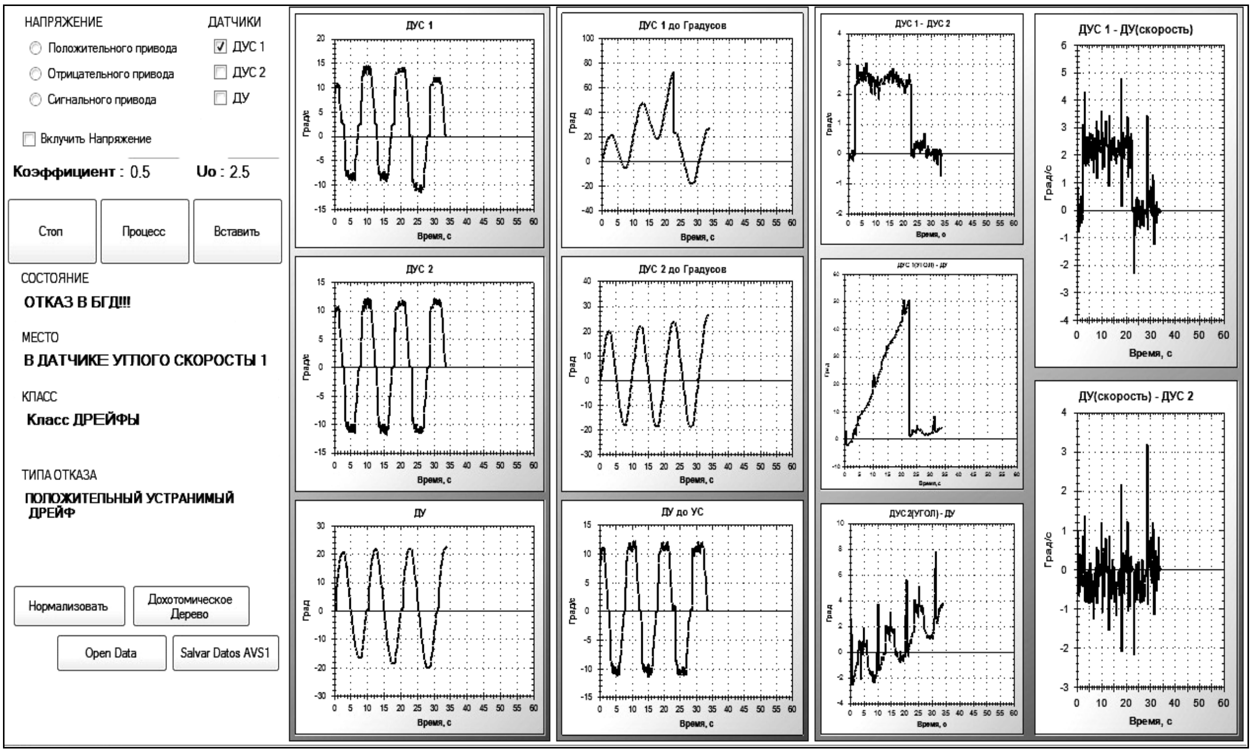

Fig. 10. Fault tolerant algorithm in a working situation

Drift-Coefficient faults are the union of these two classes of faults; therefore, twenty faults can be determined (d13-d32). In order to identify which kind of fault has occurred, it must be applied (19) and then apply statements in (20).

$$\Delta\hat{U}_i = \frac{1}{k}\sum_{n=1}^{k}\hat{U}_i(n), \qquad (19)$$

where $\hat{U}_i(n)$ - values of the signal in the faulty sensor;

$\Delta\hat{U}_i$ - average value of $\hat{U}_i(n)$.

$$\begin{aligned}
&Z_{4a}\left\{= \Delta\hat{U}_i > 0\right\},\\
&Z_{4b} = Z_{4k} = \left\{\frac{\Delta K}{2} > 0\right\},\\
&Z_{4c} = Z_{4l} < \left\{10\% \cdot \frac{\Delta K}{2}\right\},\\
&Z_{4e} = Z_{4d} = Z_{4g} = Z_{4j} = Z_{4i} > \{\delta_M\}, \qquad (20)\\
&Z_{4f} = Z_{4o} = \left\{-\delta_{M\,min} \geq \frac{\Delta K}{2} \geq -\delta_{M\,max}\right\},\\
&Z_{4h} = Z_{4q} < \left\{-10\% \cdot \frac{\Delta K}{2}\right\},\\
&Z_{4m} = Z_{4n} = Z_{4p} = Z_{4r} = Z_{4s} > \{-\delta_M\},
\end{aligned}$$

where Z_{4a} – positive drift indicator;

Z_{4b}, Z_{4k} – positive changed coefficient indicators;

Z_{4c}, Z_{4l} – recoverable positive decreased coefficient indicators;

Z_{4e}, Z_{4d}, Z_{4g}, Z_{4j}, Z_{4i} – recoverable positive drift indicators;

Z_{4f}, Z_{4o} – reoriented coefficient indicators;

Z_{4h}, Z_{4q} – recoverable negative decreased coefficient indicators;

Z_{4m}, Z_{4n}, Z_{4p}, Z_{4r}, Z_{4s} – recoverable negative drift indicators;

δ_M – threshold value for unrecoverable drift;

$\delta_{Mmax,min}$ – threshold values for reoriented coefficient.

Conclusions

An extended fault tolerant algorithm has been presented. The algorithm brings up a diagnostic model for different king of possible faults that can occur in the gyroscopic sensors unit. The algorithm has been jointly tested by a developed computer program and a gyroscopic sensors unit, obtaining the expected results and diagnosing a total of 96 kinds of faults for a gyroscopic sensors unit compounded by two angular velocity sensors and one angle sensor.

The fault tolerant algorithm can recover the system when the kind of fault diagnosed permitted it.

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Поступила в редакцию 22.05.2012

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УСОВЕРШЕНСТОВАННЫЙ АЛГОРИТМ ОТКАЗОУСТОЙЧИВОСТИ ДЛЯ БЛОКА ГИРОСКОПИЧЕСКИХ ДАТЧИКОВ

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В данной статье представлен усовершенствованный алгоритм отказоустойчивости. Усовершенствование данного алгоритма, также как и его применение, рассмотрены в данной работе. Эффективность данного алгоритма была проверена с помощью компьютерной программы и применена на блоке гироскопических датчиков (БГД). Усовершенствованный алгоритм гироскопических датчиков может осуществлять диагностику БГД, постоянно отслеживая его состояние с помощью нескольких математических моделей, определяя возможность существования ошибки в блоке. Как только ошибка была обнаружена в блоке, алгоритм может найти место ошибки, позволяя нам определить, тип ошибки в блоке, а данная диагностика может помочь нам осуществить правильные действия для восстановления оптимального функционирования БГД.

Ключевые слова: система отказоустойчивости, алгоритм отказоустойчивости, блок гироскопических датчиков.

УДОСКОНАЛЕНИЙ АЛГОРИТМ ВІДМОВОСТІЙКОСТІ ДЛЯ БЛОКУ ГІРОСКОПІЧНИХ ДАТЧИКІВ

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У цій статті представлено удосконалений алгоритм відмовостійкості. Удосконалення цього алгоритму, як і його застосування представлено у цій роботі. Ефективність цього алгоритму була перевірена за допомогою комп'ютерної програми та застосована на блоці гіроскопічних датчиків (БГД). Удосконалений алгоритм гіроскопічних датчиків може здійснювати діагностику БГД, постійно відстежуючи його стан за допомогою декількох математичних моделей, визначаючи можливість існування помилки у блоці. Як тільки помилка була виявлена у блоці алгоритм може знайти місце помилки, даючи нам можливість визначити тип помилки у блоці, а ця діагностика може допомогти нам здійснити правильні дії для відновлення найліпшого функціонування БГД.

Ключові слова: система відмовостійкості, алгоритм відмовостійкості, блок гіроскопічних датчиків.

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